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Impact of Soil Insecticides on Western Corn Rootworm and Maize Yield

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Abstract The Western Corn Rootworm (*Diabrotica virgifera virgifera*) is a major pest in maize production, causing significant economic losses globally. This study investigates the biology and ecology of the Western Corn Rootworm, focusing on its life cycle, feeding behavior, and ecological adaptations, which contribute to its persistence and the development of resistance. A comprehensive analysis of various soil insecticides, including their classification, modes of action, and application methods, was conducted, and their efficacy in controlling Western Corn Rootworm populations was evaluated through field trials and experimental data. This study explores the relationship between Western Corn Rootworm infestation and maize yield loss, highlighting the long-term impact of soil insecticide use on maize productivity. It also addresses the development of resistance in Western Corn Rootworm populations and proposes management strategies to mitigate the development of resistance. Furthermore, this study discusses the impact of soil insecticides on the environment and non-target organisms, with a focus on soil health, microbial communities, and non-target species. The role of soil insecticides within an Integrated Pest Management (IPM) framework is analyzed, emphasizing the importance of combining chemical, biological, and cultural control methods. This study identifies the latest trends in soil insecticide development and application, biotechnological advancements, and research gaps, and provides recommendations for sustainable Western Corn Rootworm management practices.
Keywords Western corn rootworm (*Diabrotica virgifera virgifera*); Soil insecticides; Maize yield; Resistance development; Integrated pest management (IPM)

1 Introduction

The Western Corn Rootworm (WCR), *Diabrotica virgifera virgifera* LeConte, is a significant pest of maize, particularly in the United States and Europe. This pest primarily targets the root system of maize plants, leading to reduced water and nutrient uptake, plant instability, and ultimately, significant yield losses (Meinke et al., 2021). The WCR has a notorious reputation for its ability to develop resistance to various control measures, including chemical insecticides and genetically modified crops expressing *Bacillus thuringiensis* (Bt) proteins (Disi et al., 2018).

The economic impact of WCR on maize production is substantial. In the United States alone, the costs associated with WCR control and yield losses are estimated to exceed $1 billion annually (Fishilevich et al., 2016). The pest's ability to cause severe root damage results in significant economic losses for farmers due to decreased crop yields and increased management costs (Ferracini et al., 2021). In Europe, although the pest has not caused large-scale economic damage, it remains a serious threat, necessitating ongoing research and management efforts (Gyeraj et al., 2021).

Soil insecticides have been a critical component of WCR management strategies. Historically, various classes of insecticides, including cyclodienes, organophosphates, carbamates, and pyrethroids, have been employed to control WCR populations (Krawczyk et al., 2020). However, the extensive use of these chemicals has led to the evolution of resistance in WCR populations, reducing the efficacy of these treatments (Souza et al., 2019). Despite this, soil insecticides continue to play a role in integrated pest management (IPM) programs, often in combination with other control tactics such as crop rotation and the use of transgenic crops (Pereira et al., 2022).

The purpose of this study is to evaluate the impact of soil insecticides on WCR and maize yield. This study will synthesize current research findings on the effectiveness of various soil insecticides, the development of resistance in WCR populations, and the implications for maize yield. By providing a comprehensive overview of the existing literature, aims to inform future research and management practices to enhance the sustainability and efficacy of WCR control strategies.

2 Biology and Ecology of Western Corn Rootworm

2.1 Life cycle and behavior of WCR

The Western Corn Rootworm (WCR), *Diabrotica virgifera virgifera*, is a significant pest of maize in North America and Europe. The life cycle of WCR includes egg, larval, pupal, and adult stages. Eggs are laid in the soil during late summer and hatch in the following spring. The larvae then feed on maize roots, causing substantial damage to the plant's root system, which can lead to reduced water and nutrient uptake, increased susceptibility to lodging, and ultimately, decreased maize yield (Devos et al., 2013). The adult beetles emerge in mid-summer, feed on maize silks and leaves, and mate to lay eggs, thus completing the cycle (Gassmann et al., 2011).

2.2 Feeding habits and impact on maize plants

WCR larvae primarily feed on maize roots, which weakens the root system and diminishes the plant's ability to absorb water and nutrients. This root damage can also create entry points for fungal and bacterial pathogens, further compromising plant health and stability (Pingault et al., 2022). Severe root pruning by WCR larvae has been shown to decrease shoot dry weight and grain yields significantly (Gyeraj et al., 2021). Additionally, adult WCR beetles feed on maize silks, which can interfere with pollination and reduce kernel set, leading to further yield losses. The feeding behavior of WCR larvae and adults thus poses a dual threat to maize crops, affecting both root integrity and reproductive success (Jaffuel et al., 2019).

2.3 Ecological adaptations and resistance development

WCR has demonstrated a remarkable ability to adapt to various management strategies, including crop rotation, soil insecticides, and genetically modified Bt-maize. The pest's adaptability is partly due to its non-recessive inheritance of resistance traits, minimal fitness costs associated with resistance, and limited adult dispersal, which facilitates localized resistance development (Darlington et al., 2022). Field-evolved resistance to Bt-maize has been documented, with WCR populations showing resistance to multiple Bt toxins, including Cry3Bb1 and Cry34/35Ab1 (Gassmann, 2021). This resistance evolution is exacerbated by continuous maize cultivation and insufficient planting of refuges, highlighting the need for integrated pest management strategies that combine multiple tactics to delay resistance development and ensure sustainable WCR management (Blandino et al., 2017).

3 Types of Soil Insecticides Used Against WCR

3.1 Classification of soil insecticides

Soil insecticides used against the Western Corn Rootworm (WCR) can be broadly classified into several chemical classes, including organophosphates, pyrethroids, and neonicotinoids. Organophosphates, such as terbufos and isofenphos, have been traditionally used due to their effectiveness in controlling WCR larvae by inhibiting acetylcholinesterase, an essential enzyme for nerve function (Modic et al., 2020). Pyrethroids, including bifenthrin, tefluthrin, and cyfluthrin, act on the nervous system of insects by modifying the gating kinetics of sodium channels, leading to paralysis and death (Souza et al., 2019). Neonicotinoids, such as clothianidin and thiacloprid, target nicotinic acetylcholine receptors in the insect nervous system, causing overstimulation and eventual death (Alford and Krupke, 2018).

3.2 Mode of action of different insecticides

The mode of action of these insecticides varies significantly. Organophosphates work by inhibiting acetylcholinesterase, leading to the accumulation of acetylcholine and continuous nerve impulse transmission, which results in paralysis and death of the insect9. Pyrethroids affect the nervous system by delaying the closure of sodium channels, causing prolonged depolarization of the nerve membrane, which also leads to paralysis and death (Alford and Krupke, 2018). Neonicotinoids bind to nicotinic acetylcholine receptors, causing continuous stimulation of the nerves, which results in paralysis and death (Clair et al., 2020). These differences in modes of action are crucial for integrated pest management strategies, as they allow for the rotation of insecticides to manage resistance development in WCR populations (Figure 1) (Meinke et al., 2021).

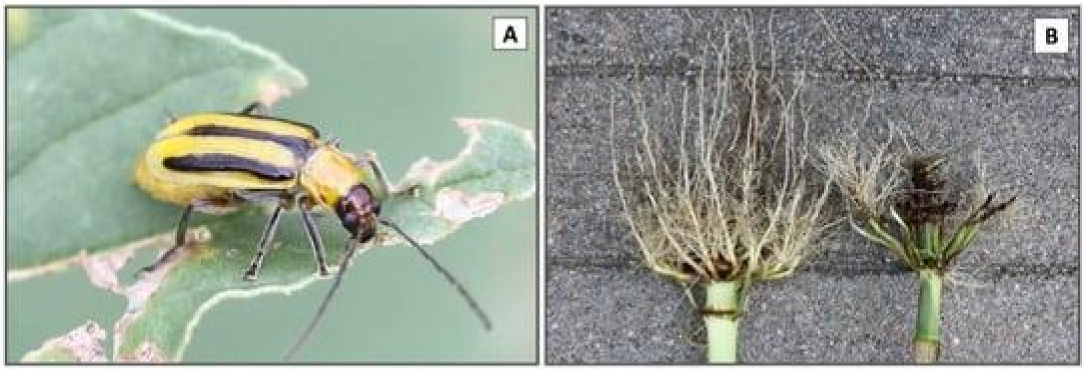

Figure 1 (A) Adult Diabrotica virgifera virgifera LeConte; (B) example of severe root injury from Diabrotica virgifera virgifera LeConte (Dvv) larval feeding that can occur when Dvv larval density is high (right) versus uninjured root (left) (Adopted from Meinke et al., 2021)

Meinke et al. (2021) found that the presence of Diabrotica virgifera virgifera LeConte, commonly known as the Western corn rootworm, poses a significant threat to corn crops due to its larval feeding behavior. The larvae of this species cause severe root injury, leading to reduced nutrient and water uptake in affected plants, which can ultimately result in stunted growth and lower crop yields. The study highlights that high larval density exacerbates the damage, making early detection and management crucial to preventing extensive agricultural losses. These findings underscore the importance of integrated pest management strategies to control Diabrotica virgifera virgifera populations and mitigate their impact on corn production.

3.3 Application methods and timing

The application methods and timing of soil insecticides are critical for their effectiveness in controlling WCR. Soil insecticides can be applied as granular formulations at planting time, which ensures that the insecticide is present in the root zone when WCR larvae hatch and begin feeding (Sutter et al., 1989). Seed treatments with systemic insecticides, such as neonicotinoids, provide protection by allowing the insecticide to be taken up by the plant and distributed throughout its tissues, including the roots (Ferracini et al., 2021). In-furrow applications at planting time are also common, ensuring that the insecticide is placed directly in the root zone (Blandino et al., 2017). The timing of application is crucial; for instance, applying insecticides at sowing has been shown to significantly reduce WCR larval density and increase grain yield. Additionally, the use of entomopathogenic nematodes and fungi in combination with chemical insecticides has been explored to enhance control and reduce the impact on non-target organisms (Rauch et al., 2017).

4 Efficacy of Soil Insecticides on WCR Control

4.1 Evaluation of various soil insecticides in controlling WCR populations

The application of soil insecticides has been shown to significantly reduce the population of Western Corn Rootworm (WCR) larvae, which are known to cause substantial damage to maize crops by feeding on the roots. In a study conducted over four years in Northern Italy, the use of soil insecticides at different planting times resulted in a 43% reduction in WCR larval density and a 65% decrease in root injury, leading to an 8% increase in grain yield (Blandino et al., 2017). Similarly, field trials in Nebraska, USA, demonstrated that soil insecticides effectively protected maize roots from WCR damage in areas with pyrethroid-susceptible populations, although their efficacy was reduced in regions with pyrethroid-resistant WCR populations (Souza et al., 2019). Another study in Central Europe compared the effectiveness of soil-applied granular insecticides, seed treatments, and entomopathogenic nematodes, finding that all treatments significantly decreased the number of emerging WCR beetles and increased maize plant weights (Modic et al., 2020).

4.2 Field studies and experimental data on insecticide performance

Field studies have consistently shown that soil insecticides can effectively control WCR populations and mitigate root damage. For instance, a two-year study in Northern Italy evaluated different chemical control strategies and found that both seed-applied and in-furrow soil insecticides significantly reduced WCR larval density and increased grain yield by up to 19% (Ferracini et al., 2021). In another study, the combined application of entomopathogenic nematodes and chemical insecticides in Austria resulted in the lowest number of WCR adults and minimal root damage, although grain yield was not significantly affected compared to untreated controls (Rauch et al., 2017). Additionally, a three-year field experiment in Slovenia demonstrated that soil-applied tefluthrin and entomopathogenic nematodes were equally effective in reducing WCR beetle emergence and increasing maize plant weights (Figure 2) (Furlan et al., 2022).

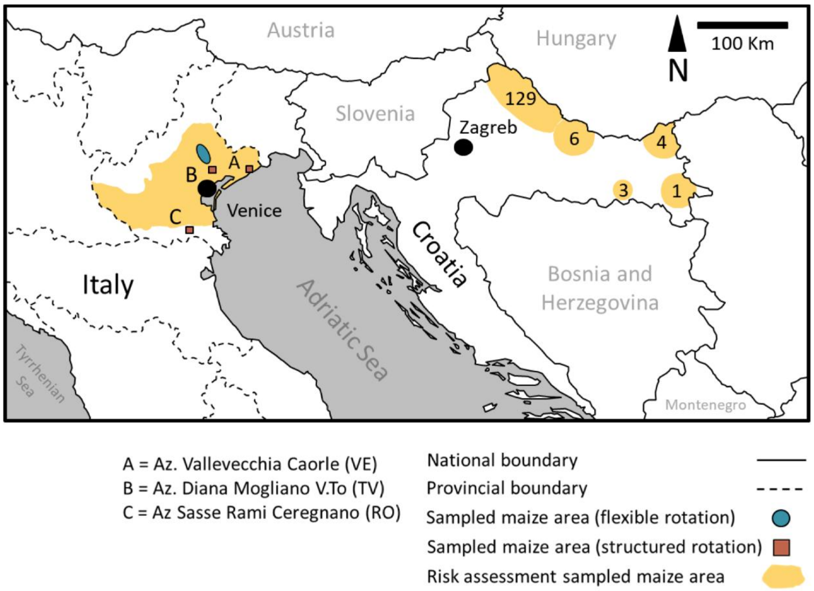

Figure 2 Map showing the regions in Italy and Croatia surveyed for WCR damage between 2003 and 2017 (Adapted from Furlan et al., 2022)

Image capton: The locations of Venice and Zagreb are indicated by black circles. Orange coloring indicates areas surveyed for risk factors in Italy and Croatia. The numbers associated with surveyed areas in Croatia indicate the numbers of fields that were monitored. In Veneto, Italy, monitored fields were distributed throughout the entire maize cultivation area. Red symbols indicate the areas in Italy where farmers applied structural crop rotation and the blue symbol indicates the area where farmers applied flexible crop rotation. In Croatia, no comparisons of crop rotation regimes were conducted (Adapted from Furlan et al., 2022)

Furlan et al. (2022) investigated the impact of different crop rotation strategies on the management of Western Corn Rootworm (WCR) damage across regions in Italy and Croatia. Their study highlighted significant regional differences in agricultural practices, with structured crop rotation being more prevalent in certain areas of Italy, particularly in regions such as Veneto. This structured approach was contrasted with the flexible rotation strategies employed in other areas, which allowed for adjustments based on specific conditions and crop requirements. The research underscored the importance of tailored agronomic strategies in mitigating WCR damage and suggested that the lack of comparison between crop rotation regimes in Croatia may have implications for the effectiveness of pest management practices in that region. The study's findings emphasize the need for ongoing risk assessment and adaptation of crop management practices to local conditions to optimize pest control efforts.

4.3 Factors influencing the efficacy of soil insecticides

The efficacy of soil insecticides in controlling WCR populations can be influenced by several factors, including soil type, application rate, and environmental conditions. For example, the effectiveness of soil insecticides was found to be consistent across different planting times and soil types in Northern Italy, suggesting that these factors did not significantly impact insecticide performance (Jaffuel et al., 2019). However, in Nebraska, the presence of pyrethroid-resistant WCR populations significantly reduced the efficacy of soil-applied bifenthrin and tefluthrin, highlighting the importance of considering resistance levels when selecting insecticides. Additionally, a study in Slovenia indicated that soil conditioners mixed with entomopathogenic nematodes could enhance the persistence and effectiveness of biological control agents in different soil types. Environmental conditions, such as temperature and moisture levels, can also affect the performance of soil insecticides, as demonstrated by varying results in field trials conducted over multiple years and locations (Meinke et al., 2021). In conclusion, soil insecticides have proven to be effective in controlling WCR populations and reducing root damage in maize crops. However, their efficacy can be influenced by factors such as resistance levels, soil type, and environmental conditions. Integrating soil insecticides with other management strategies, such as crop rotation and biological control agents, may enhance their effectiveness and contribute to sustainable WCR management.

5 Impact on Maize Yield

5.1 Relationship between WCR infestation levels and maize yield loss

The impact of soil insecticides on maize yield is multifaceted, involving the relationship between Western Corn Rootworm (WCR) infestation levels and maize yield loss, a comparative analysis of maize yield with and without soil insecticide application, and the long-term effects of soil insecticide use on maize productivity. WCR infestation levels have a direct and significant impact on maize yield loss. The larvae of WCR feed on maize roots, which impairs the plant's ability to uptake water and nutrients, leading to reduced plant vigor and yield. Studies have shown that higher densities of WCR eggs correlate with increased root damage and subsequent yield loss. For instance, untreated plots with higher egg densities experienced significant yield reductions, while insecticide-treated plots showed less yield loss, indicating the critical role of managing WCR populations to protect maize yield (Ferracini et al., 2021). Additionally, root pruning by WCR larvae has been linked to decreased shoot dry weight and grain yields, further emphasizing the detrimental effects of WCR on maize productivity (Kahler et al., 1987).

5.2 Comparative analysis of maize yield with and without soil insecticide application

The application of soil insecticides has been shown to significantly improve maize yield compared to untreated controls. In various studies, soil-applied insecticides led to a reduction in WCR larval density and root damage, resulting in higher grain yields. For example, insecticide-treated plots exhibited an 8% increase in grain yield at physiological maturity compared to untreated plots (Modic et al., 2020). Similarly, the use of different chemical control strategies, including pyrethroid, neonicotinoid, and organophosphate insecticides, resulted in a maximum grain yield increase of up to 19% compared to untreated controls. These findings highlight the effectiveness of soil insecticides in mitigating WCR damage and enhancing maize yield.

5.3 Long-term effects of soil insecticide use on maize productivity

The long-term use of soil insecticides has shown consistent benefits in terms of maize productivity. Over multiple years and varying environmental conditions, soil insecticides have consistently reduced WCR larval density and root damage, leading to sustained yield improvements. For instance, a four-year study in Northern Italy demonstrated that soil-applied insecticides provided a steady yield advantage, with a positive yield increase observed in 95% of the production situations evaluated. Additionally, the persistence of entomopathogenic nematodes in soil for extended periods has been shown to provide long-term control of WCR larvae, further supporting the sustainable use of biological control agents alongside chemical insecticides (Blandino et al., 2017). However, it is important to consider the potential for resistance development in WCR populations, as evidenced by reduced efficacy of certain soil insecticides in areas with pyrethroid-resistant WCR populations (Souza et al., 2019). Therefore, integrated pest management strategies, including crop rotation and the use of multiple control tactics, are recommended to maintain the long-term effectiveness of soil insecticides and ensure sustainable maize productivity (Furlan et al., 2022).

6 Resistance Development in WCR

6.1 Mechanisms of resistance development in WCR populations

The western corn rootworm (WCR), Diabrotica virgifera virgifera, has demonstrated a remarkable ability to develop resistance to various control measures, including Bt maize and soil insecticides. The mechanisms underlying this resistance are multifaceted. For instance, resistance to Bt maize has been linked to non-recessive inheritance, minimal fitness costs, and limited adult dispersal. Additionally, oxidative and hydrolytic metabolism have been implicated in resistance to organophosphate, carbamate, and pyrethroid insecticides, facilitating cross-resistance between these classes. Laboratory studies have shown that WCR populations can evolve resistance to Bt toxins such as Cry3Bb1 and Cry34/35Ab1, with some populations displaying resistance to all commercially available Bt traits (Gassmann et al., 2011). Esterase activity has also been identified as a potential resistance mechanism, with significant elevation observed in resistant populations.

6.2 Case studies of resistance evolution in different regions

Field-evolved resistance to Bt maize by WCR has been documented in various regions, particularly in the U.S. Corn Belt. The first cases of resistance were reported in Iowa in 2009, where WCR populations had been exposed to Cry3Bb1 maize for multiple consecutive years. Subsequent studies confirmed that these populations exhibited significantly higher survival rates on Cry3Bb1 maize compared to non-resistant populations (Souza et al., 2019). In Nebraska, field trials revealed that pyrethroid-resistant WCR populations significantly reduced the efficacy of soil-applied insecticides such as bifenthrin and tefluthrin. Another study in Phelps County, Nebraska, demonstrated that resistance to methyl parathion in adult WCR also conferred resistance in larvae, although not to all organophosphate insecticides. These case studies highlight the rapid and widespread evolution of resistance in WCR populations across different regions.

6.3 Management strategies to delay or prevent resistance

To delay or prevent the development of resistance in WCR populations, integrated pest management (IPM) strategies are essential. These strategies include rotating fields out of maize production, using soil-applied insecticides with non-Bt maize, and planting refuges of non-Bt maize (Gassmann, 2021). The combination of Bt maize with conventional insecticides has been shown to be ineffective in increasing yield or reducing root injury, suggesting that a more integrated approach is necessary (Petzold-Maxwell et al., 2013). Additionally, early detection and mitigation of resistance through adaptive IRM approaches and proactive, integrated IRM-pest management strategies are crucial. Reducing reliance on single Bt traits and employing a multitactical approach can help mitigate resistance evolution and prolong the effectiveness of current and future transgenic technologies (Gassmann et al., 2019).

7 Environmental and Non-target Effects

7.1 Impact of soil insecticides on soil health and microbial communities

The application of soil insecticides to control the western corn rootworm (WCR) has significant implications for soil health and microbial communities. Studies have shown that while soil insecticides can effectively reduce WCR larval density and subsequent root damage, they may also impact the soil's microbial ecosystem. For instance, the use of synthetic insecticides such as tefluthrin and bifenthrin has been associated with alterations in soil microbial populations, potentially disrupting beneficial microbial interactions that are crucial for soil health (Blandino et al., 2017). Additionally, the persistence of these chemicals in the soil can lead to long-term changes in microbial community structure, which may affect nutrient cycling and soil fertility7. On the other hand, biological control methods, such as the application of entomopathogenic nematodes and beneficial bacteria like Pseudomonas, have shown promise in managing WCR populations while promoting soil health. These biological agents not only target WCR larvae but also enhance plant growth and resilience by fostering beneficial microbial communities (Modic et al., 2020).

7.2 Non-target effects on beneficial insects and other soil organisms

The use of soil insecticides can have unintended consequences on non-target organisms, including beneficial insects and other soil-dwelling organisms. Beneficial insects such as pollinators and natural predators of pests can be adversely affected by exposure to soil-applied insecticides. For example, the application of tefluthrin and bifenthrin has been shown to reduce the populations of non-target soil organisms, which play essential roles in maintaining soil health and ecosystem balance (Souza et al., 2019). Moreover, the disruption of these beneficial organisms can lead to secondary pest outbreaks, further complicating pest management efforts. In contrast, biological control methods, such as the use of entomopathogenic nematodes and beneficial bacteria, have been found to be more selective, targeting WCR larvae while minimizing harm to non-target species. These biological agents can coexist with beneficial soil organisms, thereby preserving the ecological functions they perform.

7.3 Environmental concerns and mitigation measures

The environmental concerns associated with the use of soil insecticides for WCR management are multifaceted. The persistence and mobility of these chemicals in the soil can lead to contamination of water bodies through runoff and leaching, posing risks to aquatic ecosystems and human health. Additionally, the development of insecticide resistance in WCR populations necessitates the use of higher doses or more potent chemicals, exacerbating environmental impacts (Meinke et al., 2021). To mitigate these concerns, integrated pest management (IPM) strategies that combine chemical, biological, and cultural control methods are recommended. Crop rotation, for instance, has been shown to effectively reduce WCR populations without the need for insecticides, thereby minimizing environmental impacts. Furthermore, the adoption of biological control agents, such as entomopathogenic nematodes and beneficial bacteria, offers a sustainable alternative that can reduce reliance on chemical insecticides while promoting soil health and biodiversity (Jaffuel et al., 2019). Implementing these IPM strategies can help balance effective WCR management with environmental conservation.

8 Integrated Pest Management (IPM) Strategies

8.1 Role of soil insecticides within an IPM framework

Soil insecticides play a crucial role within an Integrated Pest Management (IPM) framework for controlling the Western Corn Rootworm (WCR). These insecticides are often used as a complementary tactic alongside other management strategies to manage annual densities of WCR and mitigate crop injury. Historically, the extensive use of soil and foliar insecticides has led to the evolution of resistance in WCR populations, necessitating their integration with other IPM tactics to delay resistance development and maintain their efficacy. Field studies have shown that soil-applied insecticides can significantly reduce WCR larval density and root damage, leading to increased maize yield. However, the over-reliance on chemical control methods alone can lead to resistance, making it essential to incorporate these insecticides within a broader IPM strategy that includes crop rotation, biological control, and other cultural practices (Blandino et al., 2017).

8.2 Combining chemical, biological, and cultural control methods

Combining chemical, biological, and cultural control methods is essential for effective WCR management within an IPM framework. Crop rotation has been identified as one of the most effective cultural practices for reducing WCR populations below damage thresholds without the need for insecticides. Biological control methods, such as the application of entomopathogenic nematodes and beneficial soil organisms like arbuscular mycorrhizal fungi and Pseudomonas bacteria, have shown promise in reducing WCR damage and enhancing maize yield. These biological agents can be used in conjunction with chemical treatments to provide a more sustainable and environmentally friendly approach to pest management. For instance, the combined application of soil insecticides and biological agents has been found to be as effective as chemical treatments alone, offering a viable alternative for WCR control6. Integrating these methods can optimize pest control, reduce the risk of resistance development, and minimize environmental impacts (Meinke et al., 2021).

8.3 Case studies of successful IPM programs for WCR management

Several case studies have demonstrated the success of IPM programs in managing WCR populations and improving maize yield. In Italy and Croatia, long-term surveys and field research have shown that crop rotation, both structural and flexible, effectively keeps WCR populations below damage thresholds without the need for insecticides (Furlan et al., 2022). Another successful example is the use of entomopathogenic nematodes and beneficial soil organisms in Missouri, USA, where these biological agents significantly reduced root damage and increased grain yield in WCR-infested maize fields (Figure 3) (Jaffuel et al., 2019). Additionally, a meta-analysis of insecticide efficacy trials in Indiana, USA, highlighted the importance of integrating neonicotinoid seed treatments with other IPM strategies to manage WCR effectively while reducing costs and minimizing non-target effects (Alford and Krupke, 2018). These case studies underscore the importance of a holistic approach to pest management that combines chemical, biological, and cultural methods to achieve sustainable and effective WCR control.

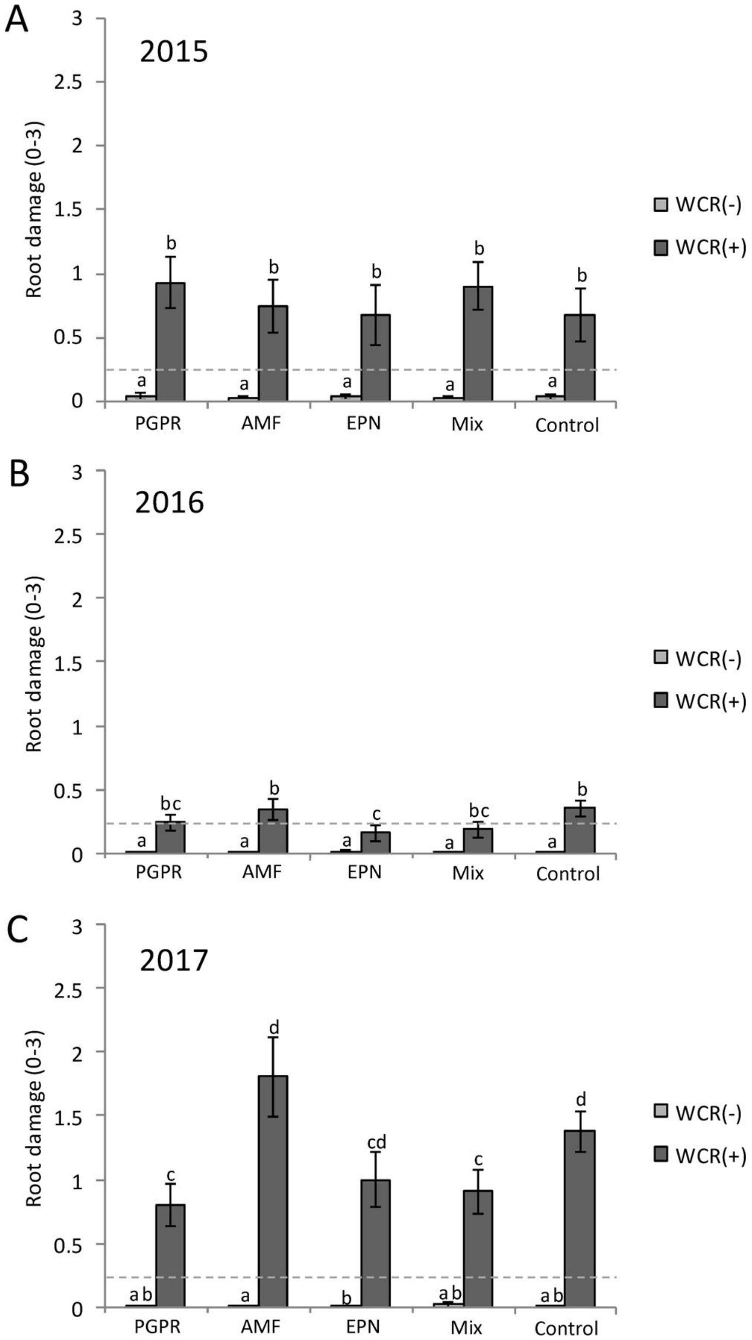

Figure 3 Root damage measured on the node-injury scale depending on the beneficial organisms applied and the western corn root worm (WCR) infestation status (Adapted from Jaffuel et al., 2019)

Image capton: (A) in 2015, (B) in 2016 and (C) in 2017. The dash line represents the economical threshold of root damage. PGPR: plant-growth promoting rhizobacteria, EPN: entomopathogenic nematodes, AMF: arbuscular mycorrhizial fungi, Mix: PGPR + EPN + AMF. Bars represent mean percentage ± SE. Means denoted by different letters are significantly different ($P < 0.05$, Fisher's least significant difference test) (Adapted from Jaffuel et al., 2019)

Jaffuel et al. (2019) found that the application of beneficial organisms, such as plant-growth promoting rhizobacteria (PGPR), entomopathogenic nematodes (EPN), and arbuscular mycorrhizal fungi (AMF), had varying effects on reducing root damage caused by Western Corn Rootworm (WCR) across different years. In 2015, all treatments resulted in significant reductions in root damage compared to the control. However, the effectiveness of these treatments varied in subsequent years. By 2016, AMF showed a slightly higher root damage level compared to the other treatments, while in 2017, AMF led to the highest root damage among all treatments. This suggests that while biological control agents can be effective, their impact may fluctuate depending on environmental conditions and WCR pressure, highlighting the need for adaptive management strategies in pest control.

9 Future Directions and Research Needs

9.1 Emerging trends in soil insecticide development and application

Recent studies have highlighted the importance of developing and applying soil insecticides in innovative ways to combat the Western Corn Rootworm (WCR). For instance, the application of soil insecticides at different maize planting times has shown significant reductions in WCR larval density and root injury, leading to increased maize yield (Blandino et al., 2017). Additionally, the efficacy of various chemical control strategies, including pyrethroid, neonicotinoid, and organophosphate insecticides, has been evaluated, with seed-applied insecticides like clothianidin and tefluthrin showing promising results in increasing grain yield. However, the emergence of pyrethroid-resistant WCR populations necessitates a multitactical approach to manage resistance and prolong the effectiveness of soil insecticides.

9.2 Advances in biotechnological approaches for WCR control

Biotechnological advancements offer promising alternatives to traditional chemical insecticides. RNA interference (RNAi) technology has emerged as a novel method for WCR management. This technology involves maize expressing double-stranded RNA structures that target essential genes in WCR, leading to insect death. The first in planta RNAi product targeting the WCR *snf7* gene, combined with Bt proteins, has been approved for commercial use, marking a significant step forward in species-specific pest management. Additionally, the combined application of beneficial soil organisms, such as arbuscular mycorrhizal fungi, *Pseudomonas bacteria*, and entomopathogenic nematodes, has shown potential in promoting plant growth and protecting against WCR infestations (Jaffuel et al., 2019).

9.3 Research gaps and priorities for future studies

Despite the progress made, several research gaps and priorities need to be addressed to enhance WCR management strategies. One critical area is the need for long-term studies to evaluate the persistence and effectiveness of biocontrol agents like entomopathogenic nematodes in different soil types and climatic conditions (Modic et al., 2020). Furthermore, the impact of root pruning by WCR larvae on nutrient content in maize and its subsequent effects on plant health and yield require further investigation. Another priority is the development of integrated pest management (IPM) strategies that combine crop rotation, biotechnological approaches, and chemical control to sustainably manage WCR populations and reduce reliance on insecticides. Finally, economic evaluations of different pest management approaches, including neonicotinoid seed treatments and other prophylactic insecticides, are essential to determine their cost-effectiveness and guide decision-making for maize producers (Kahler et al., 1985).

10 Conclusion

The impact of soil insecticides on Western Corn Rootworm (WCR) and maize yield has been extensively studied, revealing significant findings. Soil insecticides have been shown to effectively reduce WCR larval density and root damage, leading to increased maize yield. For instance, the application of soil insecticides at different planting times resulted in a significant reduction in WCR larval density by 43%, root injury by 65%, and an increase in grain yield by 8%. Similarly, various chemical control strategies, including pyrethroid, neonicotinoid, and organophosphate insecticides, have demonstrated significant reductions in WCR larval density and increases in grain yield, with seed-applied clothianidin and tefluthrin showing yield increases of up to 19%. However, the long-term use of insecticides has led to the evolution of resistance in WCR populations, necessitating the integration of other management tactics.

For maize growers and pest management practitioners, these findings underscore the importance of using soil insecticides as part of an integrated pest management (IPM) strategy. While soil insecticides can provide immediate benefits in terms of reduced root damage and increased yield, reliance solely on chemical control can lead to resistance development. Therefore, it is crucial to incorporate other practices such as crop rotation, which has been shown to effectively keep WCR populations below damage thresholds without the need for insecticides. Additionally, the use of biological control agents like entomopathogenic nematodes has shown promise as a sustainable alternative to chemical insecticides, providing comparable efficacy in reducing WCR larval populations and enhancing maize yield.

To ensure sustainable WCR management, it is recommended that maize growers adopt a multitactical approach that includes crop rotation, the use of biological control agents, and the judicious application of soil insecticides. This integrated approach can help mitigate the risk of resistance development and prolong the effectiveness of available control measures. Furthermore, ongoing research into new technologies such as RNA interference (RNAi) offers potential future solutions for WCR management, providing species-specific pest control with reduced environmental impact. By combining these strategies, maize growers can achieve effective and sustainable management of WCR, ensuring long-term productivity and profitability.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Alford A., and Krupke C., 2018, A meta-analysis and economic evaluation of neonicotinoid seed treatments and other prophylactic insecticides in indiana maize from 2000-2015 with IPM recommendations, Journal of Economic Entomology, 111(2): 689-699. https://doi.org/10.1093/jee/tox379

Bažok R., Lemić D., Chiarini F., and Furlan L., 2021, Western corn rootworm (*Diabrotica virgifera virgifera* LeConte) in Europe: current status and sustainable pest management, Insects, 12(3): 195. https://doi.org/10.3390/insects12030195

Blandino M., Ferracini C., Rigamonti I., Testa G., Saladini M., Jucker C., Agosti M., Alma A., and Reyneri A., 2017, Control of western corn rootworm damage by application of soil insecticides at different maize planting times, Crop Protection, 93: 19-27. https://doi.org/10.1016/J.CROPRO.2016.11.006

Clair C., Norris E., Masloski K., Coats J., and Gassmann A., 2020, Evaluation of pyrethroids and organophosphates in insecticide mixtures for management of western corn rootworm larvae, Pest Management Science, 76(11): 3871-3878. https://doi.org/10.1002/ps.5938

Darlington M., Reinders J., Sethi A., Lu A., Ramaseshadri P., Fischer J., Boeckman C., Petrick J., Roper J., Narva K., and Vélez A., 2022, RNAi for western corn rootworm management: lessons learned, challenges, and future directions, Insects, 13(1): 57. https://doi.org/10.3390/insects13010057

Devos Y., Meihls L., Kiss J., and Hibbard B., 2013, Resistance evolution to the first generation of genetically modified Diabrotica-active Bt-maize events by western corn rootworm: management and monitoring considerations, Transgenic Research, 22: 269-299. https://doi.org/10.1007/s11248-012-9657-4

Disi J., Kloepper J., and Fadamiro H., 2018, Seed treatment of maize with *Bacillus pumilus* strain INR-7 affects host location and feeding by Western corn rootworm, Diabrotica virgifera virgifera, Journal of Pest Science, 91: 515-522. https://doi.org/10.1007/s10340-017-0927-z

Ferracini C., Blandino M., Rigamonti I., Jucker C., Busato E., Saladini M., Reyneri A., and Alma A., 2021, Chemical-based strategies to control the western corn rootworm, *Diabrotica virgifera virgifera* LeConte, Crop Protection, 139: 105306. https://doi.org/10.1016/j.cropro.2020.105306

Fishilevich E., Vélez A., Storer N., Li H., Bowling A., Rangasamy M., Worden S., Narva K., and Siegfried B., 2016, RNAi as a management tool for the western corn rootworm, *Diabrotica virgifera virgifera*, Pest Management Science, 72(9): 1652-1663. https://doi.org/10.1002/ps.4324

Furlan L., Chiarini F., Contiero B., Benvegnù I., Horgan F., Kos T., Lemić D., and Bažok R., 2022, Risk assessment and area-wide crop rotation to keep western corn rootworm below damage thresholds and avoid insecticide use in european maize production, Insects, 13(5): 415. https://doi.org/10.3390/insects13050415

Gassmann A., 2021, Resistance to Bt maize by western corn rootworm: effects of pest biology, the pest-crop interaction and the agricultural landscape on resistance, Insects, 12(2): 136.
https://doi.org/10.3390/insects12020136

Gassmann A., Petzold-Maxwell J., Keweshan R., and Dunbar M., 2011, Field-evolved resistance to bt maize by western corn rootworm, PLoS ONE, 6(7): e22629.
https://doi.org/10.1371/journal.pone.0022629

Gassmann A., Shrestha R., Kropf A., Clair C., and Brenizer B., 2019, Field-evolved resistance by western corn rootworm to Cry34/35Ab1 and other *Bacillus thuringiensis* traits in transgenic maize, Pest Management Science, 76(1): 268-276.
https://doi.org/10.1002/ps.5510

Gyeraj A., Szalai M., Pálinkás Z., Edwards C., and Kiss J., 2021, Effects of adult western corn rootworm (Diabrotica virgifera virgifera LeConte, Coleoptera: Chrysomelidae) silk feeding on yield parameters of sweet maize, Crop Protection, 140: 105447.
https://doi.org/10.1016/j.cropro.2020.105447

Jaffuel G., Imperiali N., Shelby K., Campos-Herrera R., Geisert R., Maurhofer M., Loper J., Keel C., Turlings T., and Hibbard B., 2019, Protecting maize from rootworm damage with the combined application of arbuscular mycorrhizal fungi, *Pseudomonas bacteria* and entomopathogenic nematodes, Scientific Reports, 9: 3127.
https://doi.org/10.1038/s41598-019-39753-7

Kahler A., Olness A., Sutter G., Dybing C., and Devine O., 1985, Root damage by western corn rootworm and nutrient content in maize, Agronomy Journal, 77: 769-774.
https://doi.org/10.2134/AGRONJ1985.00021962007700050023X

Krawczyk K., Foryś J., Nakonieczny M., Tarnawska M., and Bereś P., 2020, Transmission of *Pantoea ananatis*, the causal agent of leaf spot disease of maize (*Zea mays*), by western corn rootworm (Diabrotica virgifera virgifera LeConte), Crop Protection, 105431.
https://doi.org/10.1016/j.cropro.2020.105431

Meinke L., Souza D., and Siegfried B., 2021, The use of insecticides to manage the western corn rootworm, Diabrotica virgifera virgifera, leconte: history, field-evolved resistance, and associated mechanisms, Insects, 12(2): 112.
https://doi.org/10.3390/insects12020112

Modic Š., Žigon P., Kolmanič A., Trdan S., and Razinger J., 2020, Evaluation of the field efficacy of heterorhabditis bacteriophora poinar (rhabditida: heterorhabditidae) and synthetic insecticides for the control of western corn rootworm larvae, Insects, 11(3): 202.
https://doi.org/10.3390/insects11030202

Pereira A., Geisert R., and Hibbard B., 2022, Maize inbred Mp708 is highly susceptible to western corn rootworm, *Diabrotica virgifera virgifera* (coleoptera: chrysomelidae), in field and greenhouse assays, Journal of Insect Science, 22(6): 8.
https://doi.org/10.1093/jisesa/ieac067

Petzold-Maxwell J., Meinke L., Gray M., Estes R., and Gassmann A., 2013, Effect of Bt maize and soil insecticides on yield, injury, and rootworm survival: implications for resistance management, , 106(5): 1941-1951.
https://doi.org/10.1603/EC13216

Pingault L., Basu S., Vellichirammal N., Williams W., Sarath G., and Louis J., 2022, Co-transcriptomic analysis of the maize-western corn rootworm interaction. Plants, 11(18): 2335.
https://doi.org/10.3390/plants11182335

Rauch H., Steinwender B., Mayerhofer J., Sigsgaard L., Eilenberg J., Enkerli J., Zelger R., and Strasser H., 2017, Field efficacy of *Heterorhabditis bacteriophora* (Nematoda: Heterorhabditidae), *Metarhizium brunneum* (Hypocreales: Clavicipitaceae), and chemical insecticide combinations for Diabrotica virgifera virgifera larval management, Biological Control, 107: 1-10.
https://doi.org/10.1016/J.BIOCONTROL.2017.01.007

Souza D., Peterson J., Wright R., and Meinke L., 2019, Field efficacy of soil insecticides on pyrethroid-resistant western corn rootworms (*Diabrotica virgifera virgifera* LeConte), Pest Management Science, 76(2): 827-833.
https://doi.org/10.1002/ps.5586

Sutter G., Fisher J., Elliott N., and Branson T., 1989, Effect of insecticide treatments on root lodging and yields of maize in controlled infestations of western corn rootworms (Coleoptera : Chrysomelidae), Journal of Economic Entomology, 83: 2414-2420.
https://doi.org/10.1093/JEE/83.6.2414

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